Footprints of the Newly-Discovered Vela Supernova in Antarctic Ice Cores?

C.P. Burgess[a] and K. Zuber[b]

[a] *Physics Department, McGill University*

3600 University St., Montréal, Québec, CANADA, H3A 2T8.

[b] *Lehrstuhl für Exp. Physik IV, Universität Dortmund*

44221 Dortmund, GERMANY.

Abstract

The recently-discovered, nearby young supernova remnant in the southeast corner of the older Vela supernova remnant may have been seen in measurements of nitrate abundances in Antarctic ice cores. Such an interpretation of this twenty-year-old ice-core data would provide a more accurate dating of this supernova than is possible purely using astrophysical techniques. It permits an inference of the supernova4s ^{44}Ti yield purely on an observational basis, without reference to supernova modelling. The resulting estimates of the supernova distance and light-arrival time are 200 pc and 700 years ago, implying an expansion speed of 5,000 km/s for the supernova remnant. Such an expansion speed has been argued elsewhere to imply the explosion to have been a 15 $M_\odot$ Type II supernova. This interpretation also adds new evidence to the debate as to whether nearby supernovae can measurably affect nitrate abundances in polar ice cores.

Only a handful of supernovae have exploded over the last thousand years within several kpc of the Earth. To this select group – which is summarized[1] in Table 1 – there has recently been a new addition, due to the discovery of a young supernova remnant in ROSAT X-ray data, RX J0852.0 - 4622, quite nearby [1]. This remnant has RA $8^h\,52^m$ and Declination $-46^o 22'$ (2000 epoch), and in the likely event that RX J0852.0 - 4622 is identical to the COMPTEL Gamma Ray source GROJ0852-4642 it should be around 200 pc away, with its light potentially first arriving at Earth as early as 700 years ago [2].

Although there is no visual record of this supernova, its proximity to the Earth suggests it might have left other calling cards which might yet be found. To pursue this we have searched the literature on geophysical supernova signatures. It is the purpose of this letter to point out that supernova RX J0852.0 - 4622 indeed appears to have left its mark, through its influence on the nitrate abundances in twenty-year-old ice cores which were drilled at the South Pole station.

Date	Name	RA (1950)	Dec (1950)	Visual Magnitude	Distance (kpc)
1006 3 April	—	15 10	−40	−9.5	1.3
1054 4 July	Crab	05 40	+20	−4	2.2
1181 6 August	—	01 30	+65		2.6
1572 8 November	Tycho	00 20	+65	−4	2.7
1604 8 October	Kepler	17 30	−20	−3	4.2

Table (1): Supernovae observations within the last millenium.

In their original publication [4], the drillers of this ice core identified within it three distinctive spikes in the nitrate abundance, whose dates of deposition correspond to the dates of the three latest supernova listed in Table I. (Their core sample was not sufficiently deep to contain those of 1054 or 1006.) These spikes are easily seen in Fig. 1, which is

[1] The more recent supernova Cassiopeia A of around 1680 appears not to have been widely seen, if it was seen at all [3].

reproduced from Ref. [4]. Also seen in Fig. 1 is a fourth clear spike in the nitrate abundance, which could not be attributed to any supernova known at the time. It is remarkable that this fourth spike corresponds precisely with the time when light – including X- and gamma rays – from the recently-discovered Vela supernova would have been arriving at the Earth!

We have found no other geophysical signals for this supernova, and our search for these unearthed an interesting controversy [4], [5], [6], [7], regarding which the recent Vela supernova may shed new light. The controversy concerns whether or not nearby supernovae can be detected by studying the concentration of nitrate deposition as a function of depth in polar ice cores. Supernovae have been argued to have produced observable changes in geophysical isotope abundances [8], and there is little question that supernovae can produce NO_3^- when the ionizing radiation they generate impinges on the atmosphere [9], [10], [11]. What is not clear is whether this source of atmospheric nitrates is detectable over other sources in ice removed from polar core samples.

The evidence given in ref. [4], that polar ice cores can register NO_3^- nitrate fluctuations of a cosmogenic origin, was supported by observations of the nitrate abundance in Antarctic ice cores taken near the Vostok station (78^o 28' S, 106 ^{o} 48' E) [6]. The authors of ref. [6] claim to find evidence for a correlation between the nitrate abundances and the cyclic variations in the solar activity. Because the overall nitrate deposition rate was found to be smaller in Vostok cores than in those from the South Pole, it was not possible to confirm at Vostok that nitrate abundances correlate with supernovae, although (by eye) some increase in the nitrate levels is roughly coincident with the times of the various observed supernovae.

The difference seen in the overall annual rate of nitrate fallout, which is lower at Vostok than at the South Pole [6], might itself be some evidence in favour of its being of cosmogenic origin. As was observed in [6], such a difference could arise if the nitrate production, were associated with aurorae in the Antarctic atmosphere. Since aurorae occur when charged particles impinge on the atmosphere, the geomagnetic field places them in a torus centred on the magnetic pole. (Ionizing bremstrahlung X-rays from these particles are also directed downwards and so ionize the atmosphere preferentially beneath the aurorae.) In the southern hemisphere this makes aurorae more abundant over the

South Pole than over the Vostok station. If the nitrates precipitate rapidly the nitrate abundance deposited on the surface could also be higher at the South Pole than at Vostok.

On the other hand, searches using Greenland ice cores in the early 1980's show no evidence for correlations between nitrate levels and supernovae [5], [7]. We have ourselves examined data for chemical depositions in ice cores taken in the early 1990's from the Antarctic Taylor Dome (77^o 48' S, 158^o 43' E — reasonably close to Vostok) [12], and no spectacular nitrate peaking appears at depths corresponding to known supernovae (although some suggestive spikes do appear in the abundances of other ions, such as Cl^-).

The controversy emerges because these observations permit two different conclusions:

1. Cosmogenic influences on ion abundances in polar ice cores are swamped by terrestrial influences; or
2. Cosmogenic sources can detectably influence glacial ion abundances, but their fallout to the surface is uneven over the Earth's surface.

To the supporters of option 1 the spikes of ref. [4] must be due to some kind of experimental error, or to some other kind of terrestrial source. Their correlation with observed supernovae would be coincidental. For the supporters of option 2 the difficulty is understanding how cores taken at some places can carry cosmogenic signals, while those take at others do not.

Here we take the point of view that the agreement between the newly-discovered supernova, RX J0852.0 - 4622, and the fourth spike in the data of ref. [4], makes coincidence a less convincing explanation for the remarkable correlation between nitrate spikes and visible supernovae. We therefore adopt the point of view of option 2, in order to see what can be learnt about cosmogenic nitrate deposition on the Earth, as well as about the properties of the supernova itself. We find that several inferences may be drawn.

1. The Smoking Gun: First and foremost, the most obvious test of option 2 consists of further examination of ice cores taken at the South Pole. Taking the spikes in the data of ref. [4] at face value means that some mechanism makes the nitrate fallout due to supernovae uneven around the globe, but has not removed the most recent signals at the

South Pole itself. Although it is logically possible that the same mechanism might prevent deeper South Pole cores from carrying the evidence of the earlier supernovae of 1054 and 1006, this possibility seems unlikely given the presence of the four earlier spikes. Clearly, a comparison of the nitrate levels in more ice cores – especially those taken at the South Pole which are deep enough to include these last-mentioned supernovae – would be very useful to clarify the experimental situation. Furthermore one might envisage searching for signals in the deposition rates of other chemical compunds like Cl and NH_4.

2. Dating the New SN Remnant: The age (t) and distance (d) of RX J0852.0 - 4622 may be inferred from the observed intensity (f) of the ^{44}Ti decay gamma-ray line, as well as the angular size (θ) of the supernova remnant, using

$$f = \frac{1}{4\pi d^2} \left(\frac{Y_{44}}{m_{44}\tau_{44}} \right) e^{-t/\tau_{44}}, \qquad \theta = \frac{v_m\, t}{d}, \tag{1}$$

if the ^{44}Ti yield (Y_{44}) of the supernova and the mean expansion velocity of its remnant (v_m) are known [13]. (Here $\tau_{44} \approx 90$ yr is the ^{44}Ti half life, and m_{44} is its atomic mass.) v_m may be inferred from the present velocity of the shock wave, which is in turn found from the X-ray brightness which it produces as it slams into the surrounding medium, and Y_{44} is taken from SN models. Not surprisingly, the values for t and d obtained in this way are subject to considerable uncertainty, with age estimates being potentially inaccurate by hundreds of years.

This chain of inference may be reversed if the nitrate spikes in the South Pole ice core are due to supernova RX J0852.0 - 4622, because then more information is directly available from observations. For instance, a ^{44}Ti yield of $5 \times 10^{-5}\ M_\odot$ may now be directly inferred from observations given the date of the ice core spike (using the inferred mean remnant expansion speed of 5,000 km/s), instead of being taken from numerical studies.

Alternatively, profit may be made from the much better accuracy with which the ages of the nitrate spikes in the South Pole ice core are known. In order to estimate the error in determining the age for each depth of their South Pole ice sample, Rood *et.al.* provide three possible chronologies for the same core. These indicate the date of the previously-unidentified nitrate spike to be within the range 1320 ± 20 AD. If we take the ^{44}Ti yield

from numerical models, then we may more precisely learn the expansion velocity of the supernova ejecta. The agreement of 1320 AD with the age determined from $X-$ray and $\gamma-$ray observations of the supernova remnant then indicates that the ejecta expansion velocity is close to the central value of 5,000 km/s assumed in ref. [2].

Since the ratio between the intensity of two different gamma-ray lines is independent of the distance to the SN remnant, more may be learnt by comparing the intensity of the ^{44}Ti line with the ^{26}Al line, which has also been observed. Using the half lives $\tau_{44} \approx 90$ yr $\ll \tau_{26} \approx 1.07 \times 10^6$ yr, one finds in this way

$$\frac{f_{44}}{f_{26}} = \left(\frac{\tau_{26}\, m_{26}\, Y_{44}}{\tau_{44}\, m_{44}\, Y_{26}} \right) \; e^{-t/\tau_{44}}. \tag{2}$$

A complication arises in this case because although the short ~ 90 yr halflife of ^{44}Ti ensures the observed ^{44}Ti gamma flux comes from RX J0852.0 - 4622, the 1.07×10^6 yr half-life of ^{26}Al makes it impossible to be sure that these gamma rays are not coming from the older Vela remnant rather than just from RX J0852.0 - 4622.

Two things may be learned here by assuming the ice-core date for RX J0852.0 - 4622. First, if one uses the results of numerical models to infer an upper limit, $Y_{44}/Y_{26} < 100$ (or < 10), together with the observed ^{44}Ti flux, $f_{44} = (3.8 \pm 0.7) \times 10^{-5}/\text{cm}^2/\text{s}$, then one finds a lower limit to the ^{26}Al flux from RX J0852.0 - 4622: $f_{26} > 1 \times 10^{-7}/\text{cm}^2/\text{s}$ (or $> 1 \times 10^{-6}/\text{cm}^2/\text{s}$). Alternatively, if the observed point-source flux, $f_{\text{pt}} = (2.2 \pm 0.5) \times 10^{-5}/\text{cm}^2/\text{s}$, of ^{26}Al gamma rays is assumed to be coming from RX J0852.0 - 4622, then we learn $Y_{44}/Y_{26} \approx 0.5$ (which is in agreement with ref. [13] provided $v_m = 5,000$ km/s).

3. The Nature of the Supernova Explosion:

As is argued in Ref. [14], an expansion velocity this large for the SNR argues that this was a 15 $M_\odot$ Type II supernova. Moreover an age of 700 years gives further information, as can be seen from Fig. 2. Having a relatively nearby Vela supernova of less than 250 pc, gives a ^{44}Ti yield of less than $10^{-4} M_\odot$. This disfavours a Type Ia supernova explosion within a dense region as a possible progenitor of the new Vela supernova.

Since it was so nearby, it would be worthwhile to look for other cosmogenic signals

for this supernova, such as have been proposed for the very nearby Geminga event several hundred thousand years ago [15], [16], [17], through enhancements in the abundances of radionuclides in sediments [18], [19], [20]. One might imagine even searching for signals due to the neutrino flux, since this should be as large as 10^{16} cm^{-2}s^{-1}.

4. The Distance to SN1006: As was already noticed in [2], this date for the arrival time of light from the supernova implies the supernova distance must be 200 pc, which is on the near side of the range which is allowed by the $X-$ray measurements. This makes this the closest supernovae which happened in the last millenium. Since this range was determined [1] by comparing the brightness of remnant RX J0852.0 - 4622 with the remnant of the 1006 supernova, the 1006 remnant must be about 800 pc away, which is also at the near end of its allowed range.

5. The Distance-Dependence of the Nitrate Signal: It is tempting to observe that a distance of 200 pc to RX J0852.0 - 4622 makes this supernova 10 times closer than the next nearest SN remnant listed in Table 1. This raises the question as to why the flux of ionizing radiation was not therefore 100 times as large for this supernova than for all of the others, with a correspondingly large nitrate peak. Such a large variation in amplitude is clearly not visible for the peaks in Fig. (1).

We have three reasons not to be disturbed by this naive factor of 100 in radiation intensity. First, as mentioned in the previous item, the distance estimates to the supernovae of Table (1) carry relatively large uncertainties, with the remnant of SN1006 being possibly only 4 times as distant as RX J0852.0 - 4622. Second, all supernovae are not alike and two supernovae can differ widely in their brightness even if they are equidistant. (This point is perhaps most dramatically illustrated by the nonobservation of the supernova associated with the Cass A remnant.) Third, given that some poorly-understood mechanism is required to ensure that the rate of nitrate fallout is not uniform around the globe — as must be assumed if we are to interpret the Rood *et.al.* spikes as being cosmogenic in origin — we should expect no simple connection between the size of a nitrate spike and the amount of ionizing radiation received at the Earth.

6. The Distribution of Nitrate Fallout: Finally, if the four nitrate spikes of the Rood *et.al.* core are really associated with supernovae, then it still must be understood why nitrate levels of supernova origin are unevenly deposited around the globe, and why they are larger at the South Pole than they are in Greenland and elsewhere in Antarctica.

One possibility is suggested if the ionization mechanism due to the supernova were associated with aurorae. Besides potentially explaining different nitrate deposition rates at different Antarctic sites if the settling rate is sufficiently fast, aurorae might also account for differences between the northern and southern hemispheres. For auroral production produced by protons directed to the Earth by solar flares, the conversion to NO_3^- proceeds mainly at night [21], and so at high latitudes nitrate production proceeds most abundantly during the winter. Since the five supernovae listed in Table (1) all occur between April and early October, nitrate deposition in the northern hemisphere could be less efficient if the connection between supernovae and aurora were also to cause more effective nitrate production during the southern winter.

Of course there are also several problems with this kind of mechanism, which would have to be understood. First, association with aurorae usually means the ionization is accomplished by charged particles which preferentially hit the atmosphere near the magnetic poles because they move along the magnetic field lines of the Earth. But charged particles are not likely to have reached us yet from RX J0852.0 - 4622, since cosmic rays diffuse through the interstellar medium and would take tens of thousands of years to travel the intervening 200 pc. In addition, any such aurora-based scenario must also explain the absence of a solar-cycle dependence in the deposition rate in cores taken near the north magnetic pole.

It is our hope that the remarkable correspondence between the arrival time of light from RX J0852.0 - 4622, and the date of ref. [4]'s fourth spike will stimulate further progress in understanding the nature of terrestrial signals for nearby violent astrophysical events.

Acknowledgments

This research was partially funded by N.S.E.R.C. of Canada and les Fonds F.C.A.R.

du Québec. We thank John Beacom for updating us on the supernova distances listed in Table 1.

Figure captions

Fig. 1: Orginal data on nitrate abundance as obtained by Rood *et.al.* for a South Pole ice core. Clearly visible are the spikes which can be associated to supernova explosions.

Fig. 2: Distance versus ^{44}Ti yield for two assumed lifetimes of ^{44}Ti for a given supernova 700 years ago. The distance d is determined by the gamma flux f_{44} and ^{44}Ti - lifetime using the quadratic distance dependence of the ejected ^{44}Ti mass $Y_{44} = 4\pi e^{t/\tau} m_{44} \tau f_{44} d^2$. The lifetimes used are 87.5 years (dashed line) [22] and 90.4 years (solid line) [23]. As can be seen, for reasonable distances (below 250 pc) to the new Vela supernova remnant the ^{44}Ti yield is always below $10^{-4} M_{\odot}$. This disfavours SN Ia explosions in dense regions as a possible progenitor of the new Vela supernova.

1. References

[1] Bernd Aschenbach, *Discovery of a young nearby supernova remnant*, Nature v. 396, p. 141, 1998.

[2] A.F. Iyudin *et.al.*, *Emission from ^{44}Ti associated with a previously unknown galactic supernova*, Nature v. 396, p. 142, 1998.

[3] W.B. Ashworth, *A probable Flamsteed observation of the Cassiopeia supernova*, Jour. Hist. Astron. v. 11, p. 1, 1980.

[4] Robert T. Rood, Craig L. Sarazin, Edward J. Zeller and Bruce C. Parker, *$X-$ or γ-rays from supernovae in glacial ice*, Nature, v. 282, p. 701, 1979.

[5] T. Risbo, H.B. Clausen and K.L. Rasmussen, *Supernovae and nitrate in the Greenland ice sheet*, Nature, v. 294, p. 637, 1981.

[6] Bruce C. Parker, Edward J. Zeller and Anthony J. Gow, *Nitrate fluctuations in Antarctic snow and firn: potential sources and mechanisms of formation*, Annals of Glaciology, v. 3, p. 243, 1982.

[7] Michael Herron, *Impurity sources of F^-, Cl^-, NO_3^- and SO_4^{2-} in greenland and Antarctic precipitation*, Journal of Geophysical Research, v. 87, no. C4, p. 3052, 1982.

[8] P.E. Damon, D. Kaimei, G.E. Kocharov, I.B. Mikheeva and A.N. Peristykh, *Radiocarbon production by the gamma-ray component of supernova explosions*, Radiocarbon **37** (1995) 599-604; P.E. Damon, G.E. Kocharov, A.N. Peristykh, I.B. Mikheeva and K.M. Dai, *High energy gamma rays from SN1006AD*, Proc. 24th Int. Cosmic Ray Conf., Rome 1995, v. 2, p. 311-314.

[9] M.A. Ruderman, *Science*, v. 184, p. 1079, 1974.

[10] R.C. Whitten, J. Cuzzi, W.J. Borucki and J.H. Wolfe, *Effect of nearby supernova*

explosions on atmospheric ozone, Nature, v. 263, p. 398, 1976.

[11] D.H. Clark, W.H. McCrea and F.R. Stephenson, *Frequency of nearby supernovae and climatic and biological catastrophes*, Nature, v. 265, p. 318, 1977.

[12] J.C. Stager, P.A. Mayewski, *Abrupt early to mid-Holocene climate transition registered at the equator and the poles*, Science v. 276, p. 1834-1836.;

P.A. Mayewski, *et.al.*, *Climate Change During the Last Deglaciation in Antarctica*, Science v 272, p. 1636-1638 (1996);

E.J. Steig, *et.al.Wisconsinan and Holocene climate history from an ice core at Taylor Dome, western Ross Embayment, Antarctica*, Geografiska Annaler (in review).

[13] B. Aschenbach, A.F. Iyudin and V. Schönfelder, *Constraints of age, distance and progenitor of the supernova remnant RX J0852.0 - 4622 / GRO J0852-4642*, Astronomy and Astrophysics (to appear), (`astro-ph/9909415`).

[14] W. Chen and N. Gehrels, *The progenitor of the new COMPTEL/ROSAT supernova remnant in Vela*, Astrophysical Journal Letters v. 514, p. L103 (1999), (`astro-ph/9812154 v2`).

[15] J.P. Halpern and S.S. Holt, *Discovery of soft X$-$ray pulsations from the $\gamma-$ray source Geminga*, Nature, v. 357, p. 222, 1992.

[16] G.F. Bignami, P.A. Caraveo and S. Mereghetti, *The proper motion of Geminga's optical counterpart*, Nature, v. 361, p. 704, 1993.

[17] Daniel Wang, Zhi-Yun Li and Mitchell C. Begelman, *The X$-$ray emitting trail of the nearby pulsar PSR1929+10*, Nature, v. 364, p. 127, 1993.

[18] G. Cini Castagnoli and G. Bonino, *Thermoluminescence in sediments and historical supernovae explosions*, Il Nuovo Cimento v. 5C, n. 4, p. 488, 1982.

[19] John Ellis, Brian D. Fields and David N. Schramm, *Geological isotope anomalies as*

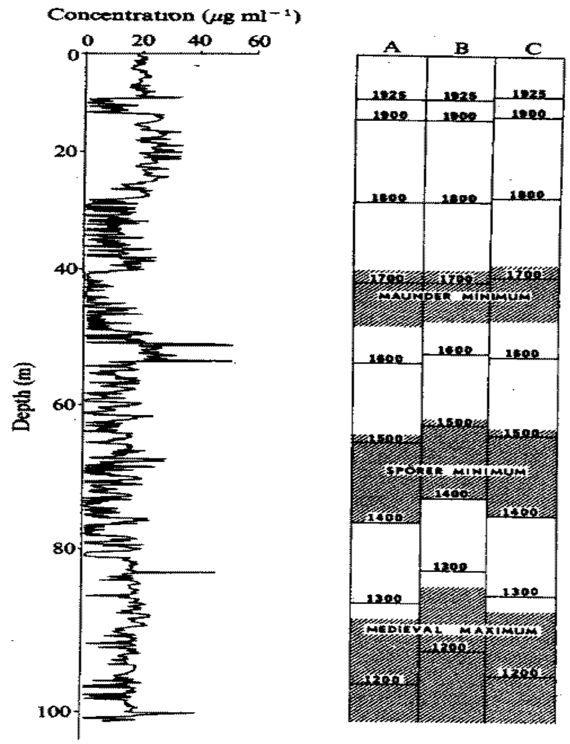
signatures of nearby supernovae, (astro-ph/9605128).

[20] Brian D. Fields and John Ellis, *On deep ocean* ^{60}Fe *as a fossil of a near-earth supernova*, preprint CERN-TH/98-373 (astro-ph/9811457).

[21] P.J. Crutzen, *Ozone production rates in an oxygen-hydrogen-nitrogen oxide atmosphere*, *Journal of Geophysical Research*, v 30, p. 7311-7327 (1976).

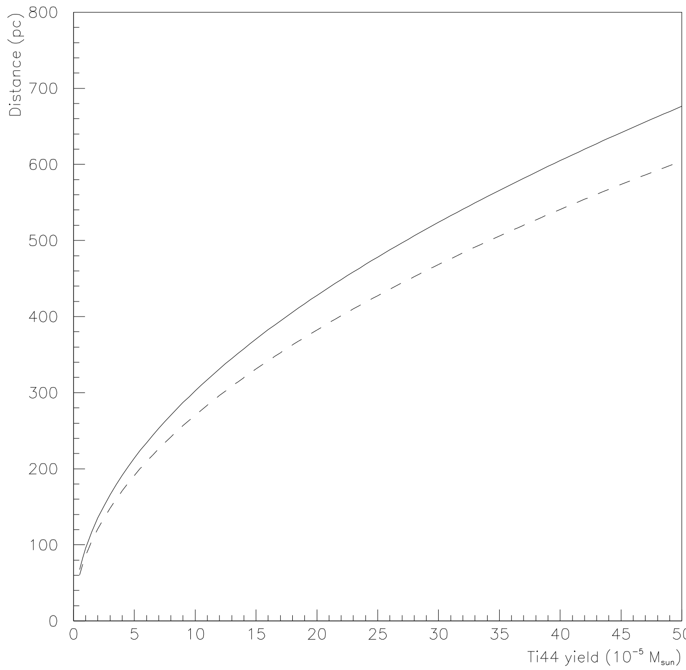
[22] F.E. Wietfeldt et al., *Long-term measurement of the half-life of* ^{44}Ti, *Phys. Rev. C*, v 59, p. 528-530 (1999).

[23] E.B. Norman et al., *Half-life of* ^{44}Ti, *Phys. Rev. C*, v 57, p. 2010-2016 (1998).



Concentration (μg ml^{-1})
0
20
40
60
Depth (m)
0
20
40
60
80
100
A
B
C
1925
1900
1800
1700
MAUNDER MINIMUM
1600
1500
SPÖRER MINIMUM
1400
1300
MEDIEVAL MAXIMUM
1200

Fig. 1



Distance (pc)
800
700
600
500
400
300
200
100
0
0
5
10
15
20
25
30
35
40
45
50
Ti44 yield (10^{-5} M_{sun})

Fig. 2